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DISTRIBUTION OF COBALT 60, ZINC 65, STRONTIUM 85, AND CESIUM 137 IN A FRESHWATER POND

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DISTRIBUTION OF COBALT 60, ZINC 65, STRONTIUM 85, AND CESIUM 137 IN A FRESHWATER POND

William A. Brungs, Jr.

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ABSTRACT

Data were obtained on the physical, chemical, and ecological distribution of four radionuclides added to a small pond. The conditions were comparable to those in an accidental release of radionuclides to an impoundment. Cobalt 60, zinc 65, strontium 85, and cesium 137 were added to a 30,000-gallon pond, with a sand substrate, and containing experimental biota. The pond was lined with a single 8-mil sheet of black polyethylene. Sampling from the pond continued for 80 days. The quantities of radionuclides were determined with a gamma-scintillation spectrometer. Supplemental chemical and biological information on the artificial pond and an adjacent control pond provided a measure of the differences between these two environments. Results of the experiment were evaluated with regard to plans for future work.

After 4 days, 10 percent of the cobalt 60, 6 percent of the zinc 65, and 5 percent of the cesium 137 remained in solution. Cobalt 60 and zinc 65 were associated principally with suspended solids, and cesium 137 with bottom sediments.

In general, soft parts of biota rapidly accumulated more radionuclides than hard parts, but gradually lost radioactivity as radionuclide concentrations in the water decreased. Clam and snail shells and fish bone usually accumulated zinc 65 and strontium 85 until almost the end of the experiment. More zinc 65 than any of the other test radionuclides was found in soft parts of biota. Strontium 85 activities usually exceeded those of zinc 65 in shell and bone.

Young clams and snails accumulated more zinc 65 and strontium 85 than did adult clams and snails. Strontium 85 concentrations in the soft parts of clams were higher in the adults. The maximum observed accumulation of strontium 85 occurred in the crayfish exoskeleton. Maximum activities of the other test radionuclides were observed in the tadpoles.

THE AUTHOR

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DISTRIBUTION OF COBALT 60, ZINC 65, STRONTIUM 85, AND CESIUM 137 IN A FRESHWATER POND

INTRODUCTION

Radioactive waste materials are being discharged from atomic energy installations and from facilities processing and utilizing radionuclides. Little information is available on the "fate" of specific radionuclides released into aquatic environments. Data on specific radionuclides are essential to an understanding of the effects of the discharge practices on the environment and the well-being of the public. This understanding is important in relation to water supply, food sources, and recreation.

Earlier determinations of the distribution of radioactivity in aquatic systems have been based frequently on gross activity. Such data are of little use in explaining the specific distribution of a mixture of several radionuclides. These may be chemically and biologically dissimilar, resulting in differences in ion exchange, sorption, assimilation, or metabolism by the components of aquatic environments. These processes must be understood and the composition of the waste must be known before the ultimate distribution of waste radioactive materials can be predicted.

The Cooperative Studies Unit[1] has investigated the distribution of specific radionuclides discharged into the Mohawk River in New York State by the Knolls Atomic Power Laboratory, into the Clinch and Tennessee Rivers in the State of Tennessee by the Oak Ridge National Laboratories, and into Lower Three Runs in the State of South Carolina by the Savannah River Project (*1*). Comparable studies have been conducted by the Hanford Atomic

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[1] Cooperative Studies Unit, Radiological Health Research Activities, Robert A. Taft Sanitary Engineering Center, U.S. Public Health Service, Cincinnati, Ohio (1958–1963).

Products Operations (*2, 3*) and by the Oak Ridge National Laboratory (*4, 5*). The principal difficulties in these field investigations are the lack of control over the quantity and nature of the discharged wastes and the fluctuating stream hydraulics and hydrology. Under these conditions sufficient information is not available to determine accurately the mechanisms that control distribution.

Laboratory investigations have provided some degree of understanding of these factors. Research on marine systems has provided most of the knowledge on the experimental uptake of specific radionuclides. Some examples are the uptake by marine algae of zinc 65 (*6, 7*), cerium 144 (*8*), and radioactive cesium (*9*). Accumulation of specific radionuclides by marine fishes, zooplankton, and shellfish has also been the subject of much research (*10, 11*).

Significant work has provided information on the experimental uptake by components of freshwater environments (*12–15*). Distribution patterns have also been determined successfully by adding radionuclides to near-natural environments. In one situation cesium 137 was introduced into a concrete fish-rearing tank after the establishment of an aquatic community (*16*). A comparable study in England involved continuous addition of water containing strontium 90 (*17*). In the latter experiment a radiostrontium equilibrium was established. This research attempted to bridge the gap between knowledge obtained under specifically controlled laboratory conditions and that obtained under field conditions.

The pilot study reported here was undertaken to determine the relative distribution of four radionuclides added to a small pond and to resolve technical problems before designing future pond experiments. The nature of this study made it comparable to an accidental release of radionuclides to an impoundment. Four radionuclides—cobalt 60, zinc 65, strontium 85, and cesium 137—were added to a plastic-lined pond containing 30,000 gallons of water, sand substrate, and experimental biota. Sampling from the pond continued for 80 days. Supplemental chemical and biological information on the artificial pond and on an adjacent control pond provided a measure of the differences between these two environments. Aspects of the experiment were evaluated with regard to desirable modifications for future work.

METHODS AND PROCEDURES

Test Site

A pond at the Newtown Fish Farm, an Ohio Division of Wildlife Hatchery, was used for the experiment (fig. 1). Pond dimensions were 50 by 70 feet. Because of the excessive permeability of the underlying soils, it was lined with a single sheet of 8-mil black polyethylene to prevent loss of water by seepage. The black liner coincidentally prevented plant growth which could have punctured the liner. Two-inch-mesh galvanized chicken wire was laid along one dike to prevent damage by muskrats. The other dikes were originally constructed to prevent this. One to two inches of sand was spread over this wire and the pond bottom to provide a smooth bed for the plastic liner. After the liner was placed, the free edges were raised and buried around the periphery of the pond to prevent the entry of surface runoff. Thirty thousand gallons of spring water from the hatchery were then pumped into the pond 2 months before the addition of the radionuclides. During the experiment, additional spring water was added to replace that lost by evaporation. The maximum depth of the pond was about 3 feet.

A local clay, chosen initially for the pond substrate, was not used because of the high sorptive affinity of this material for several of the test radionuclides. Instead, 14 tons of washed sand was distributed over the pond bottom after adding the water. The sand contained 6 percent moisture by weight as determined by ovendrying a sample for 48 hours at 105° C. Particle size analyses showed 91.3-percent sand (>50 microns), 7.5-percent silt (2 to 50 microns), and 1.2-percent clay (<2 microns). Consequently, the substrate included approximately 13 tons of sand, 1 ton of silt, and 0.2 ton of clay.

Two wooden tanks, 8 feet by 2 feet by 2 feet, were coated on the inside with polyester resin and placed beside the pond. Test fish were maintained in these tanks as well as in the pond. Pond water was circulated through these tanks (fig. 2) after passing through disposable cellulose filters that removed particles larger than 5 microns. Filters were changed as required. A recirculating pumping system was operated continuously to hasten initial mixing of the radionuclides with the pond water and to maintain uniform radionuclide levels through the pond during the experiment (fig. 3). Water was removed from the deep end of the pond several inches below the surface by means of a 30-foot horizontal manifold with six 1½-inch openings. Two-inch downspout strainers, covered with plastic-window screening, prevented large ob-

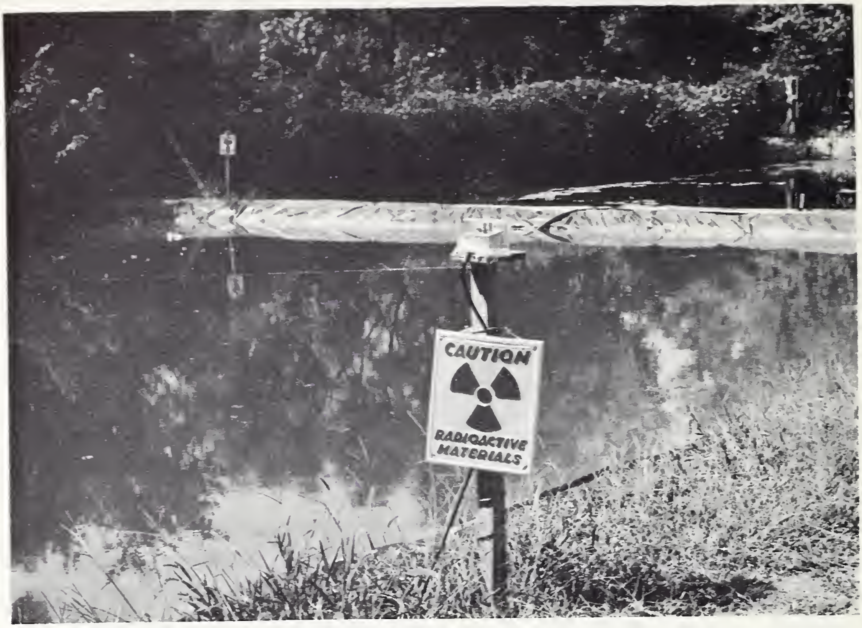

Figure 1. Experimental pond

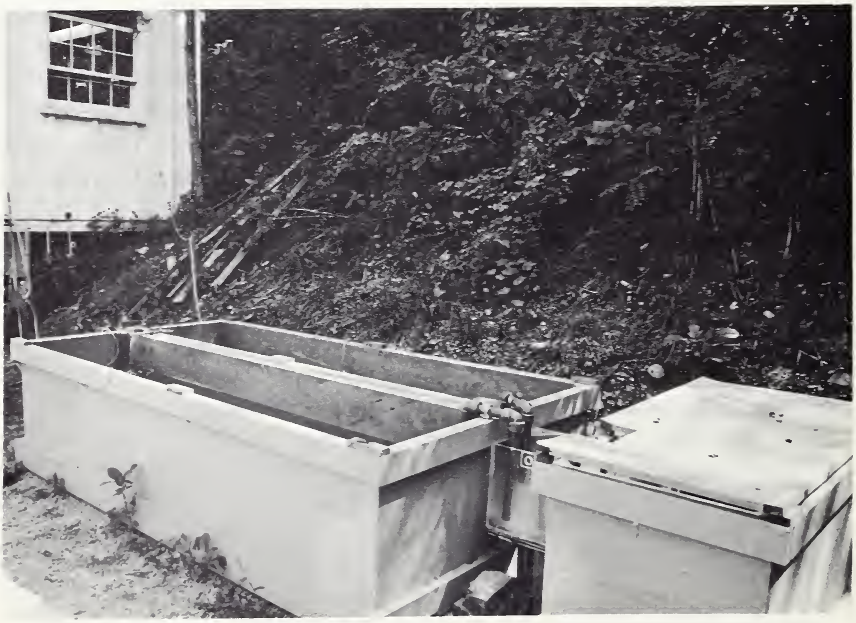

Figure 2. Holding tanks for experimental fish

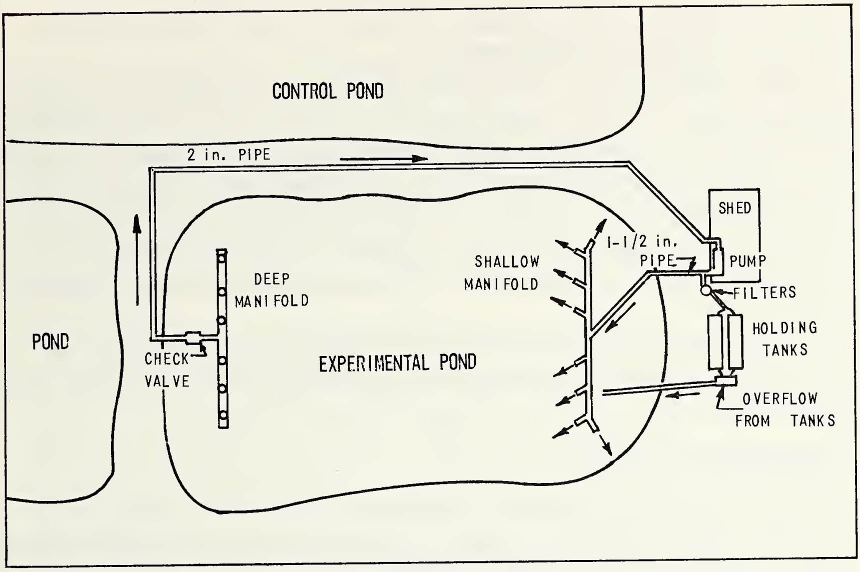

Figure 3. Pond water recirculation system

jects from entering the manifold openings and damaging the pump. A 100-foot length of 2-inch plastic pipe, with a check valve near the manifold, was connected to a pump having a rated capacity of 25 gallons per minute (gpm). A return 1½-inch plastic pipe, with a tapoff to supply water to the two fish tanks, was connected to a 20-foot return manifold in the shallow end of the pond with six horizontally directed openings to ensure complete recirculation. The pumping rate was sufficient for a daily recirculation of the pond water. An 8- by 10-foot prefabricated shed housed the pump, the temperature and light-intensity monitoring equipment, and facilities for routine water-chemistry analyses. A rain collector, measuring 4 square yards, was placed near the pond. Rain water collected was analyzed for fallout radioactivity .

Experimental Radionuclides

Cobalt 60, zinc 65, strontium 85, and cesium 137, the experimental radionuclides, were obtained from the Oak Ridge National Laboratory as chlorides in hydrochloric acid solution, except for strontium which was in the form of a nitrate in nitric acid solution. These radionuclides were chosen because of their common occurrence in radioactive wastes and because they or their short-lived daughters are gamma emitters. This choice facilitated sample preparation and analysis.

Four millicuries of each radionuclide were added to 1 liter of stock solution. At the pond site, the stock solution was added to a 50-gallon polyethylene tank containing pond water. A small pump introduced this mixture into the pond while another pump continuously added water to the polyethylene tank. The radioactive water was discharged through a plastic hose onto and under the surface of the pond. The recirculating pump completed the mixing.

The concentration of each test radionuclide in the pond water was within the limits specified for drinking water for the general population (*18*).

Experimental Samples

The macrofauna selected for this experiment is common in midwestern ponds. Two fish species, representing two feeding types, were used: the omnivorous bluegill, *Lepomis macrochirus* Rafinesque, and the bottom-feeding carp, *Cyprinus carpio* Linnaeus. *Anodonta grandis* Say, a thin-shelled species, and *Lampsilis radiata siloquoidea* (Barnes), a thick-shelled species, were the test clams. Juveniles, 3-years old or less, and adults at least 6-years old of both clam species were considered distinct sampling groups. A viviparous snail, *Viviparus malleatus* Reeve, the gastropod representative, was ideal for this study because of its large size—up to 30 grams—which enabled radionuclide analysis of individual organisms. Bullfrog tadpoles, *Rana catesbiana* Shaw, were also introduced into the pond as sample organisms. Several thousand minnows and numerous aquatic insects were placed in the pond as food for the bluegills.

Bluegills and carp were also placed in the wooden tanks. These fish were exposed to the radionuclides in water but isolated from food containing radionuclides by the filters. During the experiment these fish were fed dry fish food. By comparing radionuclide accumulation by fish in both environments, some measure of uptake by means of the natural food chain could be obtained.

Internally placed plastic tags were used to identify individual test carp. Attempts to tag bluegills were totally unsuccessful. The carp were anesthetized in a solution of MS 222 (tricaine methanesulfonate), an incision made in the body cavity, and a sterilized tag introduced. Incisions were swabbed with methylene blue to inhibit infection. No carp mortality occurred from this operation. Standard length and weight measurements were made as they were tagged.

Ninety carp were placed in the pond and 45 in one of the two tanks 1 month before adding the radionuclides. Two weeks after the carp were added, 100 adult bluegills were placed in the pond and 40 in the second tank. The carp were 1-year old and averaged 12 centimeters in standard length and 54 grams in weight at the beginning of the experiment. The terminal average weight of the bluegills was 107 grams, and the terminal average standard length was 13.5 centimeters. Weights and standard lengths were obtained for both species when they were collected during the experiment.

Individual thick-shelled clams were identified by making marks in the right and left anterior and posterior quadrants with a ¼-inch bit electric drill. Initial weights were then obtained. Weights were also obtained when the clams were sampled. These clams were placed in the pond 1 month before the start of the experiment together with the thin-shelled clams whose shells were too thin to permit marking by this method. To facilitate sampling, an attempt was made to confine the clams to the shallow end of the pond by means of barriers. Numerous clams escaped this confinement and consequently had to be collected manually by feeling over the sand bottom. Incomplete sampling resulted when an insufficient number or none of a species or age group could be found.

Approximately 400 snails were obtained from a nearby lake and placed in the pond several weeks before adding the radionuclides. Several hundred tadpoles from the hatchery ponds were added at the same time.

Pond and rain water and the substrate comprised the inorganic materials collected for radionuclide analysis.

During the experiment, self-introduced organisms were found and analyzed. They were large bullfrogs, young snapping turtles, *Chelydra serpentina* Linnaeus, and crayfish, *Orconectes rusticus* (Girard). Near the end of the experiment, small amounts of a filamentous alga, *Cladophora* sp., were collected as were fallen leaves that had settled to the bottom.

Sampling Procedures

A 2-foot fyke net placed in the pond proved unsuccessful in capturing adequate numbers of test fish. Occasionally, carp were obtained with bait but few bluegills were caught in this trap. Seining techniques were also employed and eventually the trap was removed and seining was used exclusively. Some snails, clams, and tadpoles were also caught in the seine. Additional clams and snails were obtained by feeling over the sand bottom. *Cladophora* and organic debris were similarly collected.

Substrate samples were collected from both the shallow and deep ends of the pond by scraping each sample into a 1-pint wide-mouthed plastic container. Water samples were collected from a second water tapoff in the discharge line of the circulating pump. As radionuclide concentrations in the water decreased, larger volumes were analyzed.

The total volume of rain was determined after each rainfall and 3.5 liters were retained for radionuclide analysis.

Experimental samples were collected 2, 4, 8, 12, 16, 24, 38, 52, 66, and 80 days after the radionuclides were added to the water. Additional water samples were obtained during the first week to determine any rapid distribution of radionuclides within or from this medium.

Shortly after the bluegills were placed in the pond they became infested with copepods (*Lernea* sp.). This infestation increased and 12 days after the start of the test, parasitized fish began to die. No bluegills lived longer than 24 days in the pond. Tadpoles were also parasitized to such an extent that only two were collected after 24 days in the pond. The minnows and bluegill fry (adult bluegills spawned shortly after they were placed in the pond) were also infested. Only a few of these fish were alive at the end of the experiment. Bluegills in the tank were not parasitized. The filters apparently removed all developmental stages of the copepod. No carp were observed with attached parasites.

At the end of the experiment, the carp, clams, and snails remaining in the pond were removed and placed in continuously replenished, uncontaminated water for an additional 21 days to measure radionuclide loss. These organisms were sampled weekly.

A complete set of samples was collected 3 days before dosing and analyzed to obtain baseline data on the radioactivity present in these samples before the experiment began. These data indicate the amount of naturally occurring and fallout radioactive materials that contributed to the amount of test radionuclides in all subsequent samples. The data in the tables include these background data. No baseline data were obtained for the unexpected miscellaneous samples such as frogs and algae.

Supplementary Information

To investigate the differences between the experimental pond and an adjacent normal rearing pond, various physical, chemical, and biological analyses were performed on both environments.

Water samples were collected on the same days as materials for radionuclide analysis. One set of water samples was analyzed for calcium, magnesium, iron, manganese, nitrogen, chlorides, sulfates, phosphates, total hardness, and total alkalinity. Several series of analyses were performed at the pondsite to determine acidity, dissolved oxygen, pH, total hardness, and total alkalinity. Another set of water samples was analyzed for phytoplankton content. Data are expressed as number of live cells per milliliter. Sodium and potassium concentrations were determined, as well as stable strontium and zinc. Temperature was continuously recorded at two water locations (the fish tanks and the experimental pond), and at two air locations (one in sunlight and one in shadow), by means of a multiple-speed, multiple-scan, automatic telethermometer connected to a recorder. Light intensity on the experimental pond was measured by means of a solar cell precalibrated with the same recorder.

Sample Preparation for Radionuclide Analysis

To simplify preparation, all organisms were numbered and frozen until the end of the experiment, at which time complete groups, such as all fish, were prepared.

Fish were dissected into three fractions—flesh, bone, and viscera. No attempt was made to separate intermuscular bones from the flesh. It was believed that any use of these data for evaluating human exposure from consumption of contaminated fish would necessitate a sample fraction analogous to the edible part of the fish. The flesh fraction was composed of musculature and skin; the bone fraction of scales, fins, and skeletal parts; and visceral fraction of body cavity contents (less food in stomachs), eyeballs, gill filaments, and brain. These fractional components were chosen because they were comparable to field samples prepared by this laboratory. After a thawed fish was scaled and eviscerated, the remainder was placed in aluminum foil and pressure-cooked for 1 to 2 minutes to facilitate the separation of muscle and skeletal parts.

The three fractions, in preweighed, glazed-porcelain evaporating dishes, were placed in a drying oven for about 48 hours at 105° C. Dry weight was determined, and subsequent data are expressed on a dry weight basis. Samples were then ashed overnight in a muffle furnace at 450° C. After removal from the furnace and cooling, concentrated nitric acid was added to dissolve the ash at 50° C. Samples were again placed in the muffle furnace to evaporate the acid. The resultant ash was nearly carbon-free and was dissolved in concentrated hydrochloric acid. These liquid samples were placed in 150-milliliter polyethylene containers and the volumes were made up to 35 milliliters with distilled water. This procedure provided samples of uniform volume, resulting in a constant-counting geometry.

The fish sample preparation described above was very time-consuming and hazardous. Because of the acid fumes and possible radioactive contamination of working areas and equipment by the liquid samples, dry-ash preparation was initiated. After sample separation into porcelain crucibles, fractions of the remaining organisms were dried, weighed, and ashed in the same manner as the fish. These ashed fractions, however, were ground with a pestle and placed in containers for radionuclide analysis. Small-volume samples were placed on planchets or in plastic containers similar to those used for fish samples. Large-volume samples were put in larger plastic containers.

Clams and snails were separated into shell and soft-part fractions. Shells were scrubbed to remove foreign materials, such as sand, sediment, and algal growths. A third snail fraction, composed of whole unborn young, was separated from the soft parts of the viviparous snails. Nearly all adult snails contained varying numbers and sizes of these young. Tadpole intestines with their contents and the remaining body constituted the two tadpole fractions.

Of the miscellaneous samples, only the bullfrogs and the crayfish were separated into fractions. Bullfrog fractions were bone, viscera-less-stomach contents, and flesh and skin. Crayfish were separated into exoskeleton and soft parts. Pereiopods, except for chelae and antennae, and other parts not readily separable into the two fractions, were discarded.

Sand samples were ovendried, weighed, and analyzed in plastic containers.

No preliminary preparation of the rainwater samples was made before gamma-ray analysis in 3.5-liter polyethylene well-type beakers. Pond water samples were separated into dissolved and suspended fractions by means of a continuous flow, superspeed centrifuge which removed particles with an equivalent spherical diameter of 0.7 micron and specific gravity of 2.65 or greater. The suspended fractions were placed in planchets, dried, weighed, and analyzed. The percent of organic matter in the suspended solids was determined by the Walkley-Black method (*19*). Dissolved fractions were analyzed in either plastic containers or 3.5-liter beakers, depending upon sample volume.

Sample Radionuclide Analysis

Cobalt 60, zinc 65, strontium 85, and cesium 137 all emit gamma rays during their radioactive decay. Consequently, a gamma-scintillation spectrometer was utilized for radionuclide analysis. This transistorized, 512-channel analyzer permitted a single gamma-ray analysis of each sample, since the characteristic emission energies of the radionuclides are distinct. These emission energies are: 0.513 million electron volts (MeV) for strontium 85, 0.662 MeV for cesium 137, 1.11 MeV for zinc 65, and 1.172 and 1.332 MeV for cobalt 60 (*20*). The second cobalt 60 peak (1.332 MeV) was used to determine cobalt 60. This being known, the combined peak of zinc 65 and of the lower energy cobalt 60 was corrected for cobalt 60. The remainder would then be due to zinc 65.

The detector was a solid 4- by 4-inch NaI, thallium-activated crystal optically connected to a photomultiplier tube. This unit was situated in the center of a 4 foot by 4 foot by 4 foot shield with 8-inch thick steel sides, top, and bottom. The top was opened and closed by a remote-controlled motor with a gear train. Data were printed by an electric typewriter.

Data Processing

The gamma-ray spectrometer was calibrated with standard solutions of the test radionuclides to obtain counting efficiencies for all sample containers and sample types. These efficiency factors included correction for sample geometry, Compton scattering, and photon yield. Radionuclide standards in the various sample containers were gamma scanned to calibrate the spectrometer and to calculate the interference of each radionuclide. The resulting ratios were set into a 4 by 4 matrix, and the inverse matrix coefficients were computed. These coefficients gave four linear equations, one for each radionuclide. The reliability, limitations, and accuracy of this technque have been demonstrated (*21*).

A computer program was written to resolve the four linear equations for the conversion of the observed net cpm for each radionuclide to picocuries per gram or picocuries per liter. These calculations included corrections for background, sample preparation, and container.

A second computer program was written to correct the data for radioactive decay. This was done by having the computer determine the elapsed time from the first day of the experiment to the day the sample was analyzed, and then compute the decay correction from the physical half-life of each radionuclide.

Test Water Decontamination

At the end of the study, a portable U.S. Army Corps of Engineers' water treatment unit (*22*) and a twin-bed deionizer were used to remove radionuclides from the experimental water sufficient to permit its discharge to a natural water course at lower than permissible concentrations.

Water was pumped from the pond through 1,200 feet of 1½-inch plastic pipe at a rate of 1,500 gallons per hour to the treatment equipment by means of the recirculating pump. The water passed through an iron hydroxide flocculation treatment which removed most of the suspended radioactivity. This was followed by diatomaceous-earth filtering to remove remaining suspended materials. Water was then circulated through the cation exchange resin column and the anion column.

Between each treatment in this series, water samples were collected hourly during the 19 hours required for decontamination. No water was discarded until after samples had been analyzed for the test radionuclides.

Toward the end of this process the remaining pond water and substrate were agitated by a stream of water from a fire hose and pump. This resulted in very turbid water which was used to determine the effectiveness of the treatment system in decontaminating turbid waters.

RADIOLOGICAL RESULTS AND DISCUSSION

Radionuclides in Pond Water

During the experiment there was a rapid loss of cobalt 60, zinc 65, and cesium 137 from the dissolved state but little loss of strontium 85. Radionuclide concentrations present in the dissolved and suspended solids fraction of the water samples collected during the experiment are shown in table 1.

The initial calculated concentrations, on the basis of 4 millicuries diluted in 30,000 gallons of pond water, were about 35,000 picocuries per liter for each radionuclide. The data plotted in figure 4 show the concentrations of dissolved radionuclides during the experiment. Only about 10 percent of the cobalt 60, 6 percent of the zinc 65, and 5 percent of the cesium 137 remained in solution after 4 days—assuming an initial concentration of 35,000 picocuries per liter. During this same period only 17 percent of the strontium 85 was lost from solution, partly because of the high concentration of calcium in the pond water (about 20 milligrams per liter), and the chemical similarity of these two elements.

Table 1. Radionuclide concentrations in experimental pond water samples

Days from start	Fraction	Weight of suspended solids [a]	Radionuclide concentrations pCi/liter			
			^{60}Co	^{65}Zn	^{85}Sr	^{137}Cs
0	Suspended	(19.9)	(b)	3	28	16
	Dissolved	----------	5	6	32	95
1.04	Suspended	(1.8)	9,900	7,900	180	2,500
	Dissolved	----------	16,000	35,000	60,000	26,000
1.18	Suspended	(25.2)	17,000	12,000	340	2,400
	Dissolved	----------	8,300	4,900	29,000	10,000
1.23	Suspended	(21.0)	17,000	12,000	370	3,700
	Dissolved	----------	6,700	6,600	30,000	10,000
2.25	Suspended	(18.4)	15,000	8,800	350	1,900
	Dissolved	----------	5,400	5,500	29,000	4,600
3.25	Suspended	(8.8)	13,000	5,300	260	440
	Dissolved	----------	5,500	2,200	31,000	2,600
4.25	Suspended	(14.4)	11,000	4,100	270	440
	Dissolved	----------	3,600	2,100	29,000	1,800
8.0	Suspended	(28.1)	8,200	2,600	190	460
	Dissolved	----------	3,100	1,800	30,000	600
14.0	Suspended	(9.4)	2,700	760	110	63
	Dissolved	----------	1,900	1,400	27,000	440
16.0	Suspended	(3.4)	2,400	410	99	130
	Dissolved	----------	1,600	510	26,000	490
24.0	Suspended	(17.3)	1,300	670	190	210
	Dissolved	----------	640	180	16,000	300
38.0	Suspended	(28.0)	390	640	59	340
	Dissolved	----------	560	100	12,000	150
52.0	Suspended	(23.1)	210	370	63	210
	Dissolved	----------	340	120	11,000	69
66.0	Suspended	(20.1)	120	240	43	130
	Dissolved	----------	230	100	8,200	79
80.0	Suspended	(17.6)	110	170	36	110
	Dissolved	----------	240	31	7,900	86

[a] Weight expressed in mg/liter.
[b] Less than 2 pCi/liter.

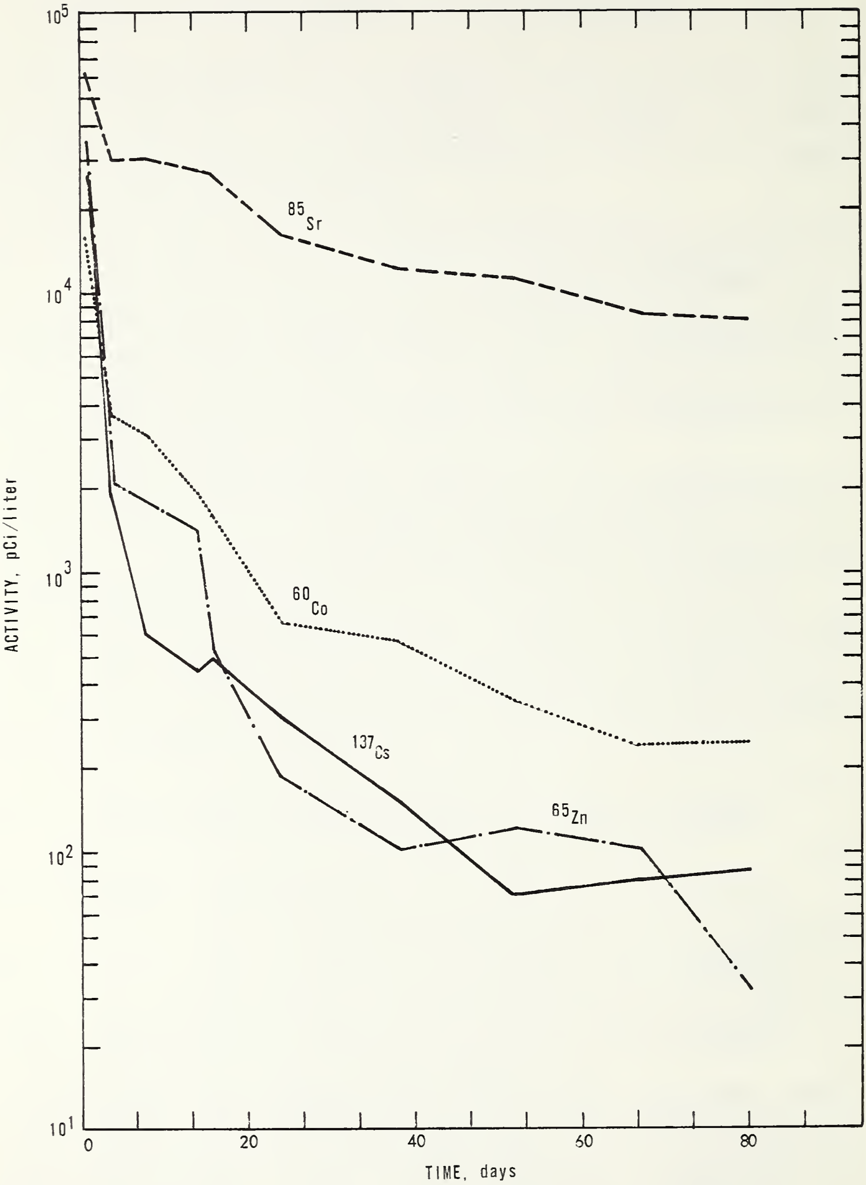

Figure 4. Activities of test radionuclides in dissolved solids fraction of pond water as a function of time

Plots of the activities of test radionuclides in the suspended solids fraction of the water during the course of the experiment are shown in figure 5. Zinc 65 and cobalt 60 were rapidly sorbed by these suspended materials. After 2 days, the concentrations of these two radionuclides in the suspended solids were two to three times those in the dissolved fractions. Cesium 137 was removed from solution more rapidly than zinc 65 or cobalt 60, but the cesium 137 concentration in the suspended solids was not as high. This was probably due to a rapid loss of cesium 137 to the inorganic materials on the pond bottom and to the suspended inorganic solids. The latter settled rather quickly after being in temporary suspension as a result of mixing during addition of the radionuclides. Cobalt 60 was probably sorbed by living and dead organic matter. Large numbers of phytoplankton were present in the experimental pond. Field data indicate that cobalt 60 is principally associated with dead organic matter (*23*). The percentages of organic matter in the suspended solids of the water are shown in table 2. The high organic content of the suspended matter and the apparent affinity of dead organic matter for cobalt 60 may help to explain why cobalt 60 concentrations in the suspended materials during the first weeks were consistently higher than concentrations of the other radionuclides. The fate of zinc 65 is partially explained by the fact that the solubility of the zinc decreases rapidly with increasing pH. Over the observed pH range (7.8 to 9.6) in the experimental pond, the solubility of zinc at the high pH was less than that (0.03 mg/l) measured in the pond at the start of the test (*24*). Consequently, much of the zinc 65 could have been precipitated and redissolved with fluctuations in the pH of the pond water. Future studies should be designed to include a constant pH recorder to compare these values periodically with zinc 65 activities over 24-hour periods. Only a small fraction of the strontium 85 in water was associated with the suspended fraction.

The distribution patterns of the four radionuclides in the pond water were quite similar to those described in reports of field studies by the Cooperative Studies Unit (*25*). In these studies strontium 90 concentrations were found to be little affected by stream environments. There were slight decreases other than by dilution over long distances. Conversely, cobalt 60, zinc 65, and radiocesium (cesium 134 and cesium 137) were rapidly lost to the surrounding environment.

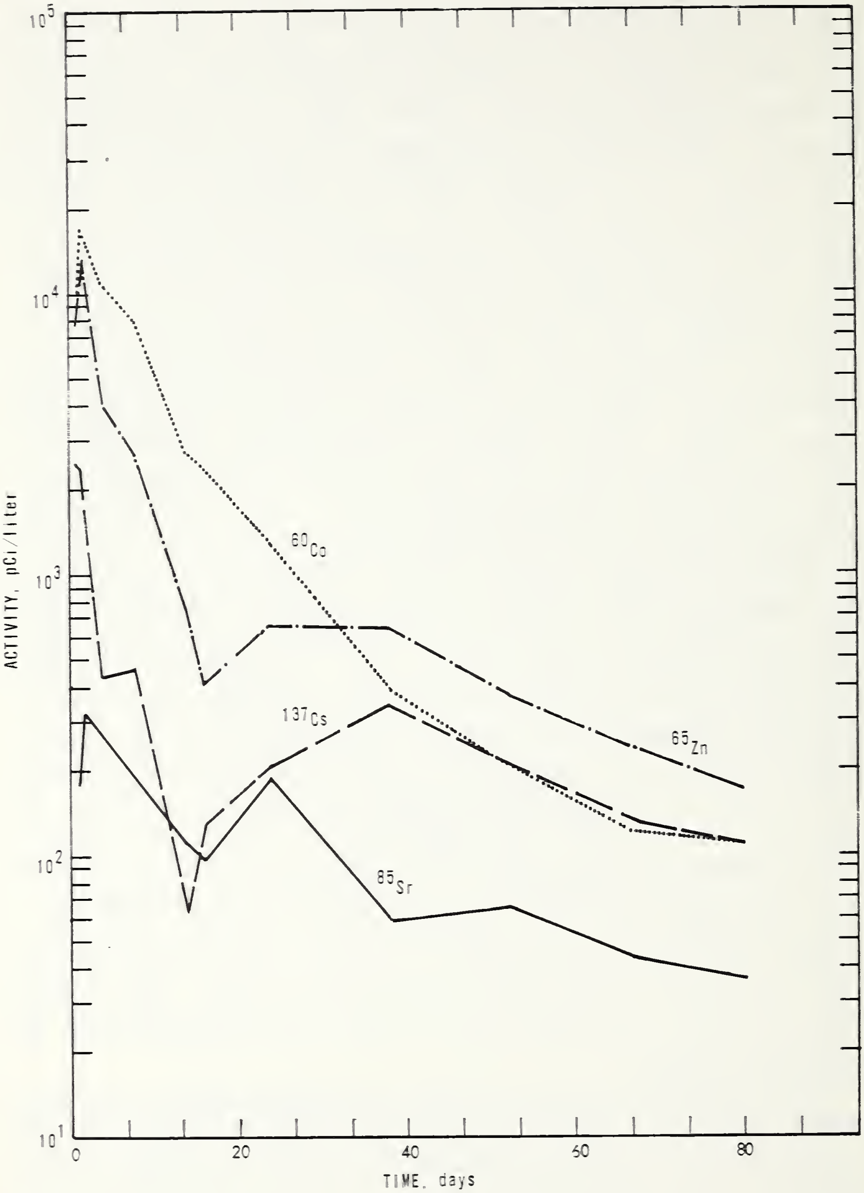

Figure 5. Activities of test radionuclides in suspended solids fraction of pond water as a function of time

Table 2. Organic composition of suspended solids fraction of pond water

Days from start	Organic matter (percent) [a]	Days from start	Organic matter (percent) [a]
0	31.2	14.0	89.3
1.04	76.6	16.0	([b])
1.18	([b])	24.0	48.6
1.23	31.9	38.0	45.2
2.25	36.2	52.0	54.6
3.25	95.7	66.0	57.1
4.25	58.3	80.0	48.0
8.00	29.8	—	—

[a] Percent by weight.
[b] Data not available.

Radionuclides in Substrate

The distribution of the test radionuclides in the substrate and clay materials will be reported in detail in a future report (*26*). Some substrate results are discussed here since more total radioactivity was associated with the substrate than with any other environmental medium.

Mean radioactivities in substrate samples are listed in table 3. After the initial radionuclide analyses, samples were washed with demineralized water to remove silt and clay. Subsequent analyses of the washed samples gave variable results, indicating incomplete removal of these fine materials. Any chemical method of separation, however, would upset the radionuclide distribution in the substrate samples.

The substrate in the deep end of the pond accumulated more radionuclides than the substrate in the shallow end because the deeper samples contained more fine sediments. Fine sediments are known to accumulate more radionuclides than coarser materials such as sand (*27*). The irregular patterns of accumulation by the substrate were partially due to variable amounts of fine sediments in the samples.

During the first week, accumulation of cesium 137 in the substrate was more rapid than that of any of the other test radionuclides. This trend was confirmed by a more rapid loss of cesium 137 from water, as compared to the loss of the other test radionuclides.

Calculations based on sample activities and the total weight of sand and finer materials, as determined by the particle size anal-

Table 3. Mean radioactivities in substrate

Days from start	Radioactivities, dry weight, pCi/g [a]			
	^{60}Co	^{65}Zn	^{85}Sr	^{137}Cs
36-inch depth:				
0	([b])	([b])	([b])	([b])
2	42	64	24	160
4	75	85	29	210
8	100	126	38	240
12	480	660	130	1,000
16	360	340	97	560
24	890	820	480	1,400
38	1,100	580	860	1,400
52	230	150	140	310
66	350	40	150	440
80	270	120	140	350
12-inch depth:				
0	([b])	([b])	([b])	([b])
2	15	22	11	69
4	79	100	33	280
8	69	89	35	180
12	150	140	66	290
16	160	130	85	250
24	210	110	150	310
38	250	240	160	360
52	230	160	140	240
66	220	180	98	370
80	270	31	190	400

[a] Means of duplicate samples.
[b] Less than 2 pCi/g.

yses previously discussed, indicate that the total substrate contained approximately four times the amount of radionuclides added to the pond. This suggests that the substrate samples were not representative and that better methods of sampling must be developed for future experiments. The poor results were probably due to stratification of radionuclides in the substrate. There were probably higher radionuclide concentrations on the surface of the substrate than in lower strata.

Bioaccumulation of Radionuclides in Fish

Mean radioactivities in experimental bluegills are shown for flesh, bone, and viscera in tables 4, 5, and 6, respectively. Because all pond bluegills not removed for analysis died within 24 days as the result of a parasitic infestation, comparisons between fish

Table 4. Mean radioactivities in flesh of bluegills

Days from start	Number of samples	Radioactivities, dry weight, pCi/g			
		^{60}Co	^{65}Zn	^{85}Sr	^{137}Cs
Tank fish:					
0	3	([a])	([a])	3	([a])
2	3	2	15	13	6
4	3	5	14	31	8
8	3	5	40	67	9
12	3	3	18	68	8
16	2	4	16	63	6
24	3	7	31	120	8
38	3	14	56	100	15
52	2	12	42	120	11
66	1	23	68	190	38
80	3	22	76	180	27
Pond fish:					
0	3	([a])	([a])	([a])	([a])
2	3	9	86	49	21
4	3	6	31	74	93
8	3	8	21	67	16
12	3	9	97	140	220
16	2	9	94	190	250
24	2	6	100	160	100

[a] Less than 2 pCi/g.

in the tank and in the pond are limited. In general, data indicate that pond fish accumulated more of each radionuclide in each of the three fractions than did fish in the wooden tanks. These differences varied from a very slight increase in cobalt 60 concentrations in bone to an almost tenfold increase in cesium 137 concentrations in flesh and bone. There was a general gradual accumulation of each radionuclide during the experiment, which indicates a slow uptake even though concentrations in the water were decreasing. Strontium 85 accumulation was greatest in the bone fraction. Templeton (*17*) has shown that, in brown trout, bone accumulates more radiostrontium than other parts of the fish, and Friend (*28*) also found higher radiostrontium levels in bone of various bottom-feeding and predatory fish. Relatively high strontium 85 accumulation (190 pCi/g) was found in flesh of bluegills in the tank. In flesh of fish in the pond, however, cesium 137 levels were highest (250 pCi/g). Zinc 65 activities were higher in the viscera than in the other fractions. The viscera include

Table 5. **Mean radioactivities in bone of bluegills**

Days from start	Number of samples	Radioactivities, dry weight, pCi/g			
		^{60}Co	^{65}Zn	^{85}Sr	^{137}Cs
Tank fish:					
0	3	(a)	(a)	(a)	(a)
2	2	4	49	110	6
4	3	4	19	200	5
8	3	4	48	380	5
12	2	3	19	570	4
16	2	6	32	570	8
24	3	7	98	870	9
38	3	13	97	930	7
52	2	11	35	670	5
66	2	20	200	1,500	18
80	3	15	81	1,100	15
Pond fish:					
0	2	(a)	(a)	(a)	(a)
2	3	5	20	170	15
4	3	8	52	390	44
8	3	6	31	460	10
12	3	6	130	960	100
16	3	27	480	970	140
24	2	6	120	680	55

[a] Less than 2 pCi/g.

the liver which is known to concentrate zinc 65 to high levels in goldfish (*29*) and brown trout (*17*). The appreciably higher accumulation of each radionuclide by pond bluegills could be attributed solely to different available food (tank fish were fed only commercial feed), if the unhealthy condition of the pond fish were not a factor.

Tables 7, 8, and 9 show the mean radioactivities found in carp flesh, bone, and viscera. Zinc 65 and strontium 85 levels were very high in carp with concentrations up to 52,000 picocuries per gram in viscera and 16,000 picocuries per gram in bone. Cesium 137 levels in all carp fractions increased for about 2 weeks and then decreased. This would indicate a short biological half-life for cesium in that the accumulation pattern is dependent on the decreasing cesium 137 activity in the water. The pattern of cesium 137 loss was less distinct in the bone, which may have a longer biological half-life than either flesh or viscera. Cesium 137 activities were higher in the pond carp than in the tank fish. The

Table 6. Mean radioactivities in viscera of bluegills

Days from start	Number of samples	Radioactivities, dry weight, pCi/g			
		^{60}Co	^{65}Zn	^{85}Sr	^{137}Cs
Tank fish:					
0	3	(a)	(a)	(a)	(a)
2	2	8	120	58	18
4	2	32	70	73	14
8	3	7	38	61	5
12	3	23	58	170	14
16	2	9	35	89	8
24	3	41	170	140	11
38	2	76	200	270	25
52	2	74	210	200	65
66	2	120	380	310	55
80	2	170	360	230	67
Pond fish:					
0	2	(a)	(a)	(a)	(a)
2	3	34	620	230	83
4	3	69	180	150	210
8	3	22	97	150	33
12	3	43	350	160	350
16	3	29	250	190	210
24	2	62	770	110	70

[a] Less than 2 pCi/g.

most definite strontium 85 uptake pattern was in the carp bone. It indicates gradual accumulation, five times greater than that in the bond of pond fish. Zinc 65 data for each fraction are variable, especially in the viscera. Highest maximum zinc 65 activity (52,000 pCi/g) was found in viscera and the lowest maximum activity (16,000 pCi/g) in flesh. If a quantity of zinc 65 were precipitated (out of the pond water) at higher pH values, it could be ingested by the carp, redissolved by acid gastric juices (*30*), and become available for absorption by the gut wall. Since the pH of the pond water does vary, the amount of precipitated zinc 65 available to the carp could vary.

The greater accumulation of zinc 65, strontium 85, and cesium 137 in pond-carp tissues than in tank-carp tissues could be attributed to differences in consumed food. The tank fish were fed a commercial feed, which may have accumulated some radioactivity if not eaten within a short time. The bluegills would not eat food that had reached the bottom of the tank. Data in table 10 show, however, that the pond carp grew much more than the tank carp,

Table 7. Mean radioactivities in flesh of carp

Days from start	Number of samples	Radioactivities, dry weight, pCi/g			
		^{60}Co	^{65}Zn	^{85}Sr	^{137}Cs
Tank fish:					
0	3	(a)	(a)	3	8
2	3	260	1,600	120	390
4	3	87	620	170	180
8	3	160	3,200	260	380
12	3	98	1,700	180	170
16	3	130	1,400	900	330
24	3	180	5,900	570	360
38	3	140	990	360	200
52	3	98	2,100	400	190
66	3	84	2,300	400	250
80	3	92	1,300	440	210
Pond fish:[b]					
0	3	(a)	(a)	(a)	(a)
2	3	35	440	150	140
4	3	34	1,000	410	290
8	3	71	5,500	460	480
12	3	100	5,600	840	1,300
16	3	39	2,900	460	970
24	3	110	12,000	1,500	610
38	3	210	12,000	1,600	640
52	1	87	7,100	840	430
66	2	140	16,000	1,400	700
80	3	150	15,000	2,200	810
87	3	100	10,000	1,600	880
94	3	144	10,000	2,000	710
101	3	170	11,000	1,600	760

[a] Less than 2 pCi/g.
[b] Carp remaining in the pond after 80 days were transferred to uncontaminated water.

which in most instances lost weight during the experiment. This growth, or lack of it, may have appreciably affected radionuclide accumulation. The relationship between strontium 85 activity in pond-carp bone and percent weight gain of each fish is shown in figure 6.

No loss of any radionuclide was apparent in the remaining carp after they were transferred to uncontaminated water. The water temperature during the 3 weeks (in uncontaminated water) was about 5° C, and the metabolic activity of these fish was much less than during the experiment, when the minimum temperature was about 19° C.

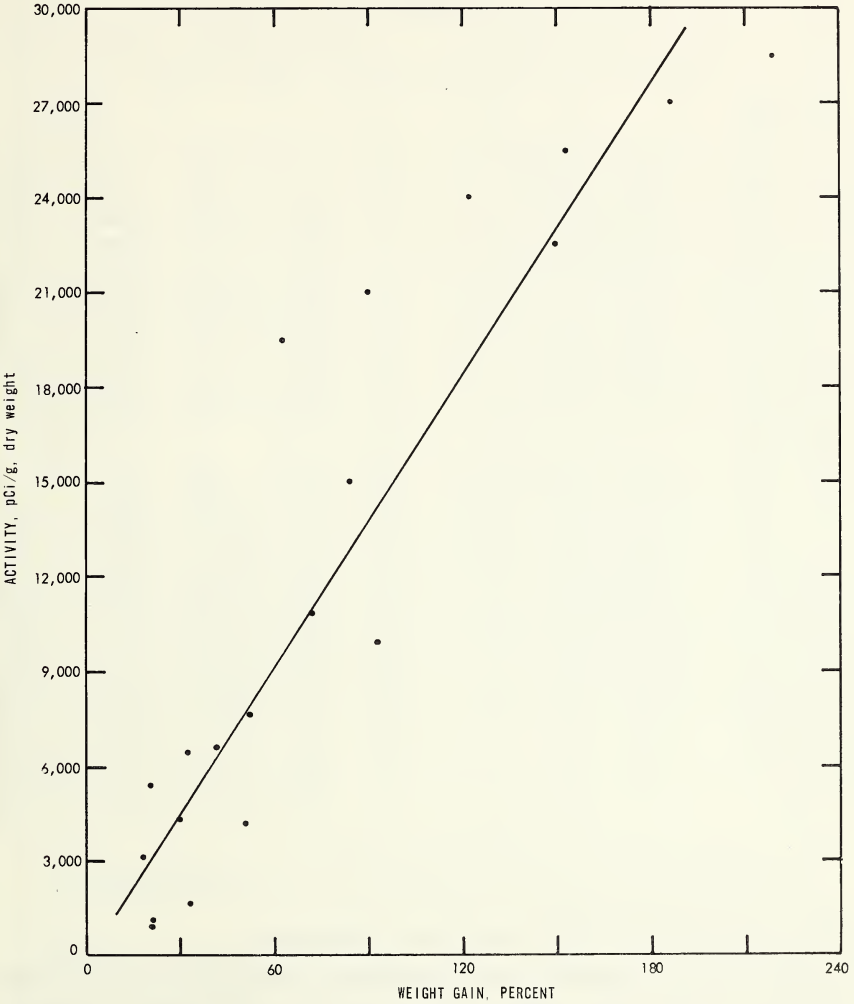

Figure 6. Relationship between strontium 85 in pond-carp bone and weight gain

Table 8. Mean radioactivities in bone of carp

Days from start	Number of samples	Radioactivities, dry weight, pCi/g			
		^{60}Co	^{65}Zn	^{85}Sr	^{137}Cs
Tank fish:					
0	3	(a)	(a)	3	(a)
2	2	85	1,300	380	210
4	3	94	830	450	120
8	3	160	6,200	1,200	190
12	2	120	4,700	1,200	170
16	3	330	6,500	2,900	260
24	3	120	5,500	2,000	170
38	3	160	1,500	2,400	83
52	2	160	5,200	4,000	140
66	3	130	4,500	3,700	160
80	3	120	2,000	2,600	80
Pond fish:[b]					
0	2	(a)	4	(a)	(a)
2	2	32	680	670	90
4	2	37	2,100	1,900	210
8	3	80	10,000	3,000	310
12	3	130	14,000	6,900	750
16	3	81	8,400	4,100	620
24	3	130	17,000	6,400	310
38	3	230	24,000	13,000	310
52	2	180	18,000	11,000	340
66	3	120	24,000	13,000	300
80	2	140	23,000	16,000	420
87	3	140	18,000	15,000	490
94	3	200	22,000	18,000	300
101	3	180	16,000	16,000	360

[a] Less than 2 pCi/g.
[b] Carp remaining in the pond after 80 days were transferred to uncontaminated water.

Bioaccumulation of Radionuclides in Tadpoles

Although no tadpoles were collected between 24 and 66 days after the experiment began, some patterns are apparent in table 11. Cesium 137 was rapidly accumulated in both fractions (gut with contents and body). This was followed by rapid and then more gradual losses. The greater cesium 137 concentrations in the gut, compared to those in the body (4.5 times higher after 66 days), are in agreement with results described by Pendleton (*31*). Tadpoles obtain much of their food from the bottom, incidentally ingesting fine inorganic materials that adsorb cesium. In the first days of the experiment probably little vertical distribution of

Table 9. Mean radioactivities in viscera of carp

Days from start	Number of samples	Radioactivities, dry weight, pCi/g			
		^{60}Co	^{65}Zn	^{85}Sr	^{137}Cs
Tank fish:					
0	3	3	5	13	5
2	2	1,200	7,700	250	640
4	3	900	4,900	530	860
8	3	1,100	16,000	790	580
12	1	840	12,000	960	630
16	3	490	11,000	710	370
24	3	750	21,000	1,000	430
38	3	520	5,000	610	200
52	3	420	11,000	400	200
66	3	300	12,000	350	210
80	3	310	5,600	420	150
Pond fish:[a]					
0	3	([b])	([b])	6	([b])
2	3	260	1,800	320	440
4	3	140	3,200	210	710
8	3	430	12,000	470	680
12	3	450	15,000	860	790
16	3	370	15,000	570	1,200
24	3	740	24,000	340	450
38	3	1,200	46,000	1,200	570
52	1	430	13,000	350	280
66	3	1,300	40,000	680	470
80	3	820	52,000	300	530
87	3	380	13,000	310	200
94	3	680	39,000	2,100	390
101	3	420	24,000	840	370

[a] Carp remaining in the pond after 80 days were transferred to uncontaminated water.
[b] Less than 2 pCi/g.

cesium 137 occurred in the sediments. Instead, it would occur as a thin layer on the substrate surface. This layer containing high cesium 137 levels eventually would mix with deeper sediments resulting in a more "dilute" cesium 137 concentration in the combination. Such a pattern would explain the cesium 137 activities in the tadpoles. Carp data demonstrated a less definite, but similar, trend.

The organic detritus, which comprises a major portion of the tadpoles' diet, apparently contained high concentrations of cobalt 60. The maximum cobalt 60 accumulation during the experiment occurred in the tadpole (16,000 pCi/g in the gut). As with ce-

Table 10. Mean weight changes in experimental carp

Days from start	Pond fish		Tank fish	
	Number of fish	Ratio [a]	Number of fish	Ratio [a]
0	3	1.24	3	0.91
2	3	1.21	2	0.94
4	2	1.41	2	0.91
8	2	1.35	3	0.93
12	2	1.60	3	0.95
16	2	1.27	3	0.96
24	2	1.83	3	1.00
38	2	2.38	3	0.95
52	2	2.38	3	1.11
66	2	2.16	3	1.10
80	3	2.29	3	0.97

[a] Ratio of final over initial weight.

sium 137, cobalt 60 maxima were observed within the first week, but cobalt 60 was lost less rapidly than cesium 137.

Zinc 65 data for tadpoles are as variable as those for carp, possibly for the same reasons, and represent the highest activities found in both tadpole fractions (56,000 pCi/g in the body and 58,000 pCi/g in the gut). No definite strontium 85 pattern is apparent other than a less rapid uptake. None of the tadpoles were in the process of metamorphosis and apparently there was little deposition of a calcareous skeleton and consequently no gradual accumulation of radiostrontium.

Bioaccumulation of Radionuclides in Snails

Activities of each radionuclide in adult snails were much higher in the soft parts than in the shells (table 12). Cobalt 60 and cesium 137 maxima were observed in both fractions within 2 weeks after dosing and were followed by gradual decreases to about 10 percent of these maxima. The high zinc 65 radioactivities in the soft parts were about 70 times those radioactivities in the shell. Maximum zinc 65 radioactivities in both fractions were observed within the first 2 weeks. There was the usual zinc 65 variability in the soft parts and a gradual loss of zinc 65 in the shell. During the first 12 days, strontium 85 accumulated rapidly in the snail soft parts. This was followed by a slight loss during the remainder of the 80 days. Strontium 85 radioactivities in the

Table 11. Mean radioactivities in tadpoles

Days from start	Number of samples	Radioactivities, dry weight, pCi/g			
		^{60}Co	^{65}Zn	^{85}Sr	^{137}Cs
Body:					
0	3	12	(a)	7	(a)
2	3	2,400	9,800	1,200	1,800
4	3	12,000	33,000	5,800	21,000
8	3	6,800	16,000	4,200	3,100
12	2	2,900	33,000	4,800	3,000
16	3	1,700	17,000	2,000	890
24	3	3,500	30,000	5,300	1,700
66	1	1,200	56,000	7,200	1,500
80	1	1,300	12,000	2,200	700
Gut:[b]					
0	3	10	17	58	(a)
2	3	10,000	33,000	5,200	39,000
4	3	10,000	40,000	6,700	21,000
8	3	16,000	30,000	4,400	14,000
12	2	11,000	41,000	8,300	7,200
16	3	11,000	58,000	22,000	13,000
24	3	10,000	35,000	11,000	9,200
66	1	4,400	23,000	5,400	6,800
80	1	3,900	13,000	3,400	6,200

[a] Less than 2 pCi/g.
[b] Gut contents were not removed.

shell gradually increased, but were always less than those levels in the soft parts.

All unborn young from each adult were included in each sample with no separation into fractions. Cobalt 60 and cesium 137 maxima (2,400 pCi/g and 2,200 pCi/g, respectively) were observed within the first week (table 13). The initial decreases following the maxima were more rapid than in the adults. Zinc 65 accumulation was variable. Strontium 85 uptake was gradual during the experiment and represented the highest radioactivities (up to 18,000 pCi/g) found in these samples. These strontium 85 levels were much higher than those in the adults and were the result of a greater proportional growth in the contaminated environment by the unborn young. No distinct decreases were evident in the snail samples that were placed in uncontaminated water after the experiment. During that time the average water temperature was about 5° C. Little normal activity and metabolism by the snails would take place at this temperature.

Table 12. Mean radioactivities in adult snails

Days from start[a]	Number of samples	Radioactivities, dry weight, pCi/g			
		^{60}Co	^{65}Zn	^{85}Sr	^{137}Cs
Soft parts:					
0	6	10	94	54	17
2	3	6,200	14,000	1,600	4,200
4	3	5,800	25,000	2,700	3,500
8	3	8,100	35,000	3,200	2,500
12	3	5,100	29,000	3,500	2,000
16	3	3,800	43,000	3,400	1,500
24	3	1,500	24,000	2,200	480
38	3	1,100	16,000	2,200	710
52	3	1,000	23,000	3,000	640
66	3	920	39,000	3,300	500
80	3	730	28,000	2,500	420
87	3	880	41,000	2,800	280
94	3	750	57,000	3,800	330
101	3	670	40,000	2,600	340
Shell:					
0	6	10	45	27	6
2	3	220	520	310	440
4	3	300	530	780	500
8	3	350	360	630	220
12	3	340	390	950	140
16	3	540	490	2,200	300
24	3	370	360	700	97
38	3	250	310	1,000	74
52	3	240	430	1,300	160
66	3	180	360	1,400	100
80	3	200	240	1,100	98
87	3	130	390	1,200	86
94	3	140	430	2,500	46
101	3	130	410	1,800	70

[a] Snails remaining after 80 days were placed in uncontaminated water.

Several small snails (weight, 3 grams) found on day 66 must have been born during the experiment since no snails of that size were placed in the pond. These were dissected into shell and soft-parts fractions and analyzed. Concentrations of each of the four radionuclides were greater in these young snails than in adults collected on the same day. Data in table 14 show that the mean zinc 65 radioactivity in the soft parts was the highest (64,000 pCi/g) in both fractions, and strontium 85 was the highest (37,000 pCi/g) in the shell.

Table 13. Mean radioactivities in unborn young of the adult snails

Days from start [a]	Number of samples	Mean number of young	Radioactivities, dry weight, pCi/g			
			^{60}Co	^{65}Zn	^{85}Sr	^{137}Cs
0	3	35	19	57	150	17
2	3	44	1,400	2,700	910	2,200
4	3	45	660	4,000	3,100	790
8	3	32	2,400	9,200	6,000	830
12	3	61	820	14,000	11,000	420
16	2	34	350	5,000	11,000	250
24	3	61	200	3,500	7,200	150
38	3	67	160	4,700	11,000	180
52	3	46	230	8,800	12,000	270
66	3	47	180	12,000	18,000	130
80	3	52	88	5,900	15,000	160
87	3	63	110	8,400	16,000	100
94	3	46	150	13,000	15,000	120
101	3	67	75	11,000	14,000	91

[a] Adult snails, which contained these young, were placed in uncontaminated water after 80 days.

Table 14. Mean radioactivities in young snails

Days from start	Number of samples	Radioactivities, dry weight, pCi/g			
		^{60}Co	^{65}Zn	^{85}Sr	^{137}Cs
Soft parts:					
66	5	2,100	64,000	12,000	1,500
Shell:					
66	4	260	1,000	37,000	72

Bioaccumulation of Radionuclides in Clams

Soft parts of oysters and scallops have been shown to concentrate zinc 65 to levels as much as 100 times those in sea water within several days (*11*). The clam soft parts accumulated more zinc 65 than the other test radionuclides, with little variability between ages or species (table 15). In *Lampsilis*, there was a rapid initial uptake during the first 2 weeks, and then slight increases until the end of the experiment. There was less zinc 65

Table 15. Mean radioactivities in soft parts of clams

Days from start [a]	Number of samples	Radioactivities, dry weight, pCi/g			
		^{60}Co	^{65}Zn	^{85}Sr	^{137}Cs
Juvenile *Lampsilis*:					
0	3	15	20	33	17
2	3	6,300	22,000	3,000	1,700
4	1	2,500	9,500	1,500	740
38	2	930	12,000	6,700	840
66	1	1,800	30,000	6,500	690
80	3	1,400	24,000	8,600	480
87	2	2,100	26,000	8,600	500
94	3	2,100	35,000	13,000	700
101	2	2,300	28,000	7,200	470
Adult *Lampsilis*:					
0	3	3	17	20	4
2	3	4,100	11,000	2,000	1,300
4	2	5,100	25,000	4,100	2,000
8	2	4,800	10,000	5,500	3,100
12	2	3,200	8,400	6,100	1,400
16	2	3,100	27,000	7,000	1,200
24	2	2,400	20,000	7,300	910
38	2	1,900	29,000	10,000	640
52	2	1,700	20,000	9,000	650
66	3	1,800	26,000	8,500	620
80	3	2,300	31,000	7,800	650
87	3	860	20,000	8,800	480
94	3	1,800	22,000	7,800	480
101	3	1,600	24,000	10,000	480
Juvenile *Anodonta*:					
0	2	7	18	40	7
38	2	2,700	20,000	6,900	510
66	3	2,100	23,000	6,700	390
80	3	2,400	24,000	7,000	620
94	1	2,600	40,000	7,000	200
101	1	2,200	25,000	6,200	120
Adult *Anodonta*:					
0	2	2	24	29	28
38	2	2,200	22,000	7,200	650
80	2	3,700	31,000	10,000	330

[a] Clams remaining after 80 days were placed in uncontaminated water.

variability in the clam soft parts than in those of the other primary consumers (snails, tadpoles, and carp). Clams filter suspended materials from the water for food rather than feed from the bottom. Consequently, the food of each clam would be more uniform and would presumably contain similar zinc 65 concentrations. The foods of the bottom-feeding primary consumers would vary, and more inorganic materials on the pond bottom would be inadvertently ingested, resulting in variable zinc 65 accumulation. The solubility relationship of zinc with pH, as discussed previously, would be a less important factor affecting zinc 65 concentration by the filter-feeding clams since they ingest only suspended materials.

The soft parts of the clams accumulated maximum levels of cesium 137 and cobalt 60 within a short time. Thereafter these levels gradually decreased. The high concentration of cobalt 60 in the soft parts was exceeded only by that found in the tadpoles and was apparently due to the large amount of living and dead phytoplankton filtered from the water.

Strontium 85 uptake was rapid initially, and continued at a reduced rate to near the end of the experiment when maxima were observed. No real differences in accumulation of cobalt 60 and zinc 65 in the soft parts were apparent between the two age groups of the two species, but more strontium 85 was present in soft parts of the older clams of both species. The soft parts of *Lampsilis* accumulated three times more cesium 137 than did *Anodonta.* Cesium 137 maxima, as mentioned above, occurred early. Because no samples of *Anodonta* could be collected before 38 days, it was expected that the observed maxima for this species would be lower than the actual maxima. After 80 days, however, both species contained similar concentrations of cesium 137 in the soft parts.

Data showing radionuclide activity in clam shells are presented in table 16. The differences in strontium 85 accumulations in the shells of the four clam groups are shown in figure 7. Strontium 85 levels were lowest in adult *Lampsilis* (the thick-shelled species). The strontium 85 levels were progressively higher in adult *Anodonta* (the thin-shelled species), juvenile *Lampsilis,* and juvenile *Anodonta.* These differences were not observed for cobalt 60, zinc 65, or cesium 137. Radioactivities were lower in the shells than in the soft parts. Cesium 137 radioactivities reached early maxima and gradually decreased after 1 week. There appeared to be a gradual accumulation of cobalt 60 in *Lampsilis.* No pattern was demonstrated by zinc 65 radioactivities.

Growth data for both age groups of *Lampsilis* are shown in table 17. Only the young of this species grew measurably during the test. This difference in growth should explain the greater accumulation of strontium 85 in the shells of juvenile *Lampsilis*

Table 16. Mean radioactivities in shells of clams

Days from start [a]	Number of samples	Radioactivities, dry weight, pCi/g			
		^{60}Co	^{65}Zn	^{85}Sr	^{137}Cs
Juvenile *Lampsilis*:					
0	3	2	2	3	(b)
2	3	49	48	48	71
4	1	66	120	42	58
38	2	55	86	2,900	12
66	1	180	200	1,900	6
80	3	110	130	2,900	5
87	2	44	86	1,100	7
94	3	74	85	790	6
101	2	90	110	1,300	5
Adult *Lampsilis*:					
0	3	(b)	2	(b)	(b)
2	3	50	63	21	15
4	2	75	80	21	14
8	2	140	420	130	140
12	2	180	190	45	38
16	2	120	80	150	18
24	2	110	44	130	13
38	2	110	180	320	33
52	2	88	66	230	8
66	3	85	100	320	9
80	3	120	94	480	12
87	3	190	170	390	12
94	3	46	46	420	5
101	3	87	95	220	11
Juvenile *Anodonta*:					
0	2	20	25	38	5
38	2	110	140	6,500	35
66	3	100	140	8,300	33
80	2	170	240	5,600	29
94	1	97	100	2,700	14
101	1	57	120	12,000	16
Adult *Anodonta*:					
0	2	9	3	25	7
38	2	170	150	760	36
80	3	170	190	2,300	31

[a] Clams remaining after 80 days were placed in uncontaminated water.
[b] Less than 2 pCi/g.

and possibly the lower strontium 85 levels in the soft parts of these young. Strontium 85 is deposited as shell by the mantle, which was included in the soft-part fraction. The differential

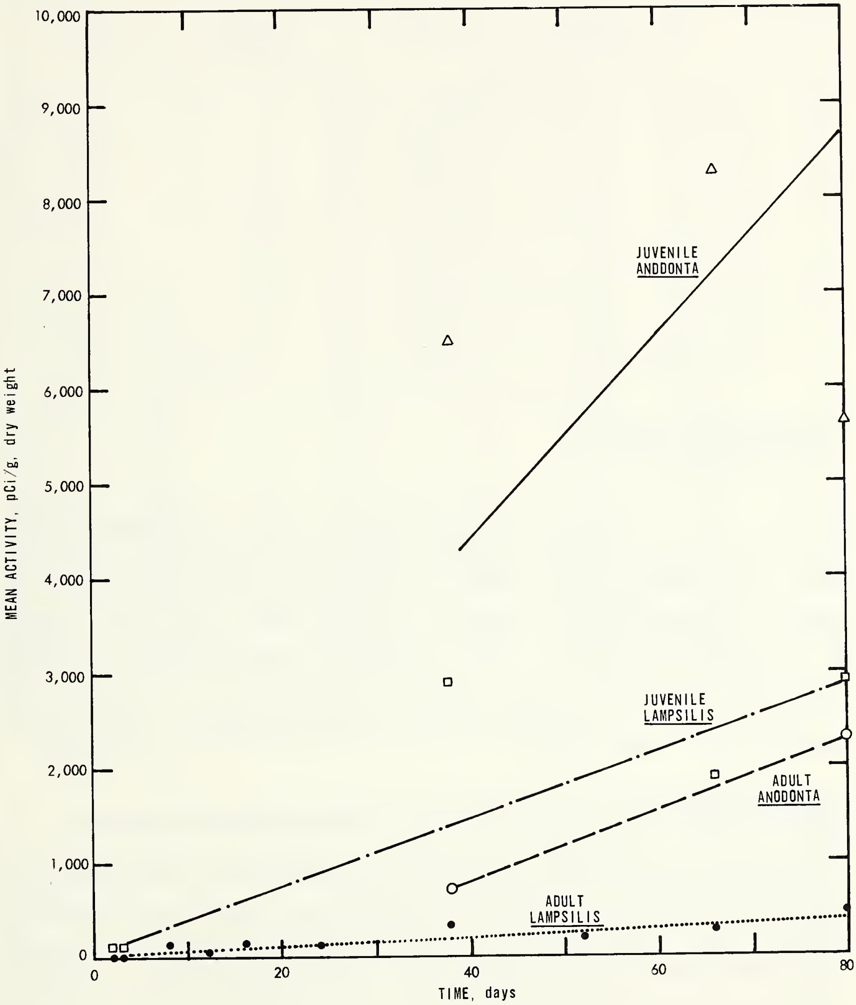

Figure 7. Strontium 85 in clam shells as a function of time

Table 17. **Mean weight changes in *Lampsilis radiata siloquoidea*** [a]

Days from start	Adult		Juvenile	
	Number of clams	Ratio [b]	Number of clams	Ratio [b]
2	3	1.00	3	1.06
4	2	1.01	1	1.01
8	2	1.02	(c)	(c)
12	2	1.01	(c)	(c)
16	2	1.03	(c)	(c)
24	2	1.02	(c)	(c)
38	2	1.01	2	1.19
52	2	0.97	(c)	(c)
66	3	1.00	1	1.18
80	3	0.98	3	1.19

[a] Thick-shelled clam species.
[b] Ratio of final over initial weight.
[c] No samples available.

uptake of strontium 85 by the shells of adult and juvenile *Anodonta* may also be due to growth differences, although no growth data were obtained. As with the carp and snails, there were no patterns of radionuclide loss by the clams after they were placed in uncontaminated water. No evidence of siphoning by the clams was observed while they were in the cold (5° C) water, and metabolic activity must have been greatly reduced. Thus, no appreciable loss was expected.

Bioaccumulation of Radionuclides in Miscellaneous Samples

Crayfish were the only miscellaneous samples in the pond from the start of the experiment to the time when they were collected. Data in table 18 indicate that algal and leaf samples accumulated more strontium 85 than other test radionuclides. This was probably due to the greater availability of this radionuclide in solution at the time these samples appeared. The filamentous algal samples contained some fine sediments which could not be removed, and which would contribute to the observed radioactivities. The highest strontium 85 radioactivity (100,000 pCi/g) of any sample organism occurred in the crayfish exoskeletons. The calcium content of the exoskeletons of this species of crayfish, *Orconectes rusticus,* in water of comparable hardness, was about 15 to 20 percent of the dry weight (*32*). The two crayfish collected probably under-

Table 18. Radioactivities in miscellaneous samples

Sample [a]	Fraction	Days from start	Radioactivities, dry weight, pCi/g			
			^{60}Co	^{65}Zn	^{85}Sr	^{137}Cs
Alga [b]	—	38	3,900	1,900	4,000	1,500
Alga	—	52	3,000	1,500	4,800	1,200
Alga	—	66	2,700	1,800	4,000	1,100
Alga	—	80	3,200	840	3,700	990
Leaves	—	52	570	1,100	5,200	440
Leaves	—	66	740	1,300	5,700	450
Leaves	—	80	400	730	3,500	310
Crayfish	Flesh	38	1,400	16,000	5,300	2,300
Crayfish	Flesh	80	760	11,000	9,500	1,100
Crayfish	Exoskeleton	38	470	4,000	100,000	880
Crayfish	Exoskeleton	80	400	2,400	100,000	610
Bullfrog	Bone	38	81	3,900	1,600	280
Bullfrog	Bone	66	2	260	110	23
Bullfrog	Bone	80	30	9,100	4,200	160
Bullfrog	Flesh	38	110	2,800	220	430
Bullfrog	Flesh	66	13	47	18	64
Bullfrog	Flesh	80	36	3,600	480	210
Bullfrog	Viscera	38	190	4,800	300	280
Bullfrog	Viscera	66	76	2,100	100	130
Bullfrog	Viscera	80	(c)	33	24	7
Turtle	Whole	66	30	76	390	95
Turtle	Whole	66	21	79	120	46

[a] Algal and leaf sample data represent means of duplicate samples. All others are single samples.
[b] *Cladophora* sp.
[c] Less than 2 pCi/g.

went a molt during the experiment when a new exoskeleton grew from inorganic materials in the environment, as well as from some that were withdrawn from the old exoskeleton prior to molt (*33*). Large amounts of strontium 85 could be accumulated under these conditions. The results of analysis of other miscellaneous samples such as frogs, turtles, and so forth, are shown in table 18.

Percent Distribution of Radionuclides in the Experimental Pond

In order to understand more fully the distribution of the four test radionuclides in the experimental pond, mass balances of each were calculated for each complete sampling day. The total radioactivity in the pond-water fractions was calculated from the measured concentrations and water volume. Total radioactivity in the biota involved a consideration of observed concentrations and the number and average size of the various groups of organisms. Miscellaneous biological samples were not included because they comprised an insignificant part of the biomass. Plankton also was not included as it, of necessity, was included in the suspended solids fraction of the water. As discussed previously, bottom sediment samples could not be used to determine the total amount of radioactivity in these materials. Consequently, the calculated value for the substrate was considered to be the difference between that amount added and that observed in the water and biota.

It should be reemphasized that the experimental pond system would be an example principally of a situation in which radioactive wastes were discharged to a standing impoundment. In a flowing system, any attempt at precise mass balances would be most difficult because of an unknown biomass and other factors. The following data will indicate that rough estimates of a mass balance could be calculated for flowing systems, at least for nonbiologically important elements, by ignoring the biota. The data resulting from these calculations are presented as percent distribution of cobalt 60 (table 19), zinc 65 (table 20), strontium 85 (table 21), and cesium 137 (table 22).

The most striking general conclusion from these calculations, from a biological point of view, was that the maximum accumulation in the biota for a single radionuclide, zinc 65, was only slightly above 1 percent. Cobalt 60 and cesium 137 never exceeded 0.25 percent. The amount of strontium 85 in the experimental

Table 19. Percent distribution of cobalt 60 in the pond

Day	Dissolved fraction of water	Suspended fraction of water	Biota	Substrate [a]
2	15	43	0.19	41.81
4	10	31	0.21	58.79
8	8.8	23	0.23	67.97
12	5.4	7.7	0.15	86.75
16	4.6	6.9	0.12	88.38
24	1.8	3.7	0.07	94.43
38	1.6	1.1	0.07	97.23
52	0.98	0.60	0.05	98.37
66	0.65	0.35	0.05	98.95
80	0.68	0.33	0.05	98.94

[a] Substrate percentage is obtained by difference.

Table 20. Percent distribution of zinc 65 in the pond

Day	Dissolved fraction of water	Suspended fraction of water	Biota	Substrate [a]
2	16	25	0.53	58.47
4	6.0	12	0.86	81.14
8	5.1	7.4	1.1	86.40
12	4.0	2.2	0.94	92.86
16	1.5	1.2	1.0	96.30
24	0.53	1.9	0.97	96.60
38	0.28	1.8	1.1	96.82
52	0.35	1.1	0.69	97.86
66	0.28	0.68	1.2	97.84
80	0.10	0.47	1.0	98.43

[a] Substrate percentage is obtained by difference.

Table 21. Percent distribution of strontium 85 in the pond

Day	Dissolved fraction of water	Suspended fraction of water	Biota	Substrate [a]
2	83	1.0	0.12	15.88
4	83	0.77	0.23	16.00
8	86	0.54	0.28	13.18
12	77	0.31	0.34	22.35
16	74	0.28	0.33	25.39
24	46	0.54	0.34	53.12
38	34	0.17	0.51	65.32
52	31	0.18	0.46	68.36
66	23	0.12	0.40	76.48
80	23	0.10	0.40	76.50

[a] Substrate percentage is obtained by difference.

biota gradually increased during the first half of the experiment and then decreased slightly. An important consideration is that the total biomass was being reduced by each set of samples. If this reduction were taken into account, there would have been a continuous increase in strontium 85 for 80 days even though the levels in the water decreased. After quick initial accumulation, the amounts of cobalt 60 and cesium 137 in the biota decreased at a more rapid rate than the removal of samples could account for.

Table 22. Percent distribution of cesium 137 in the pond

Day	Dissolved fraction of water	Suspended fraction of water	Biota	Substrate [a]
2	13	5.4	0.22	81.38
4	5.1	1.3	0.19	93.41
8	1.7	1.3	0.14	96.86
12	1.3	0.18	0.11	98.41
16	1.4	0.38	0.09	98.13
24	0.85	0.60	0.04	98.51
38	0.43	0.98	0.04	98.55
52	0.20	0.60	0.03	99.17
66	0.23	0.38	0.03	99.36
80	0.25	0.33	0.03	99.39

[a] Substrate percentage is obtained by difference.

This indicated shorter biological half-lives than for strontium 85. The zinc 65 data in table 20 demonstrate the variability previously seen in the individual samples. No pattern of decrease was apparent as the sample biomass was reduced.

Cesium 137 rapidly became associated with the substrate. After 8 days, 97 percent of the added radionuclide was associated with this medium (table 22). Cobalt 60 and zinc 65 were sorbed less rapidly, but about 99 percent of all three radionuclides (excluding strontium 85) was contained in the substrate at the end of the test. The pattern for strontium 85 in the sediments was one of gradual increase to 77 percent.

At first a much greater amount of cobalt 60 was associated with the suspended solids fraction of the water than with the dissolved fraction (table 19). Strontium 85 data in table 21 indicate the opposite pattern with very little association with the suspended solids. An alternating pattern was demonstrated by the zinc 65 data (table 20). It is felt that this was a result of the fluctuating pH previously discussed.

Fallout Radionuclides in Rainwater

Rainwater samples were collected from the time the plastic liner was put in place until the end of the experiment. The predominant fallout radionuclides were zirconium-niobium 95, ruthenium 103, ruthenium 106, cerium 141, and cerium 144. At the time of the study no routine procedure existed for quantitatively determining the amounts of each of these radionuclides present in the rain samples. The principal difficulty was that the two ruthenium and the two cerium isotopes have identical characteristic gamma-ray energies. The relative amounts of these pairs of radioisotopes present in air at Cincinnati, Ohio, during August 1962 (*34*) were used to approximate the amount of radioruthenium and radiocerium present in the rain samples. The amounts of zirconium-niobium 95 were obtained from the data in the same manner as the amounts of the test radionuclides.

Table 23 shows the microcuries of zirconium-niobium 95, radio-

Table 23. Total fallout radionuclides entering pond in rainfall

Date of rainfall	Rainfall entering pond (liters)	Total radioactivities, µCi		
		^{95}Zr-^{95}Nb	Radio-ruthenium	Radio-cerium
6/11	2,900	2.1	1.0	1.0
6/12	1,200	0.7	0.3	0.4
6/13	1,300	0.9	0.4	0.3
6/19	4,800	15.0	9.0	20.0
6/24	2,900	1.5	0.9	1.0
6/25	2,200	1.1	0.7	1.0
7/2	3,200	2.0	1.0	1.0
7/5	9,500	1.6	1.0	2.0
7/9	1,400	0.9	0.7	1.0
7/14	7,800	(a)	(a)	(a)
7/15	9,500	11.0	6.0	10.0
7/16	5,200	5.2	3.0	7.0
7/23	1,400	0.7	0.4	0.6
7/25	750	0.4	0.3	0.4
7/29	550	0.2	0.1	0.2
8/7	4,100	1.0	0.5	(b)
8/26	2,600	3.6	1.0	4.0
9/1	4,700	2.4	1.0	3.0
9/2	6,500	2.3	(b)	0.7
9/9	4,700	0.7	0.4	1.0
9/10	400	0.4	0.1	0.3
9/10	1,400	0.4	0.3	0.7
9/14	1,000	0.5	0.4	0.6
9/19	600	0.2	0.8	0.4
10/3	18,000	1.8	3.0	4.0
10/7	600	0.3	0.4	0.5
10/8	2,200	0.8	2.0	3.0
Total	101,400	57.7	34.7	64.1

[a] Sample lost before analysis.
[b] Less than 0.1 µCi.

ruthenium (ruthenium 103 and ruthenium 106), and radiocerium (cerium 141 and cerium 144) which entered the pond during each rainfall. Most of these rains occurred before the test radionuclides were added on July 30.

The total radionuclides that entered the pond with rainfall were low in comparison to those of the experimental radionuclides. Consequently, no attempt was made to take into account any effect of the fallout radionuclides on experimental uptake data other than to obtain baseline levels for experimental media. These levels were very low.

Decontamination of Experimental Pond Water

The details and results of pond-water decontamination after completion of the experiment have been published elsewhere (*35*). Only general results are discussed here.

Agitation of the bottom sediments between two decontamination runs greatly increased the amount of suspended materials in the water. The mean radioactivities for both runs, with high and low turbidities, shown in table 24, indicate no removal by filtration following coagulation and sedimentation. Most of the zinc 65 in the water of low turbidity was removed by flocculation.

Table 24. Results of pond-water decontamination [a]

Sample	Radioactivities, pCi/l			
	^{60}Co	^{65}Zn	^{85}Sr	^{137}Cs
Low turbidity: [b]				
Raw water	200	100	2,200	160
After flocculation	120	23	2,100	37
After filtration	120	19	2,100	45
After cation exchange	52	10	14	65
After anion exchange	28	8	9	23
High turbidity: [c]				
Raw water	1,300	2,000	1,700	2,400
After flocculation	350	180	1,400	78
After filtration	300	130	1,400	78
After cation exchange	45	20	20	55
After anion exchange	32	16	14	39

[a] There was no fractionation of water samples before analysis. Decontamination took place 2 months after the end of the pond study.

[b] Before suspension of sediments. The numbers are mean values of 10 hourly samples. Turbidity was about 60 on the Jackson scale.

[c] After suspension of sediments. The numbers are mean values of 9 hourly samples. Turbidity was about 1000 on the Jackson scale.

Strontium 85 was removed predominantly by the cation exchange resin which indicates that most of the strontium was in solution. Cobalt 60 and cesium 137 assumed an intermediate relationship.

The raw, turbid water of the second run contained much more silt and consequently had more radioactivity per liter. Flocculation, in this instance, removed a much greater percentage of the radioactivity, which was associated principally with the suspended matter. As before, most of the strontium 85 was dissolved. Radionuclide concentrations in the water, after all treatment processes, approximated the background levels in table 1.

SUPPLEMENTARY RESULTS AND DISCUSSION

Physical and Chemical Properties of the Experimental and Control Ponds

Results of chemical analyses of the two pond waters are shown in tables 25 and 26. Calcium and magnesium concentrations in the control pond increased slightly during the experiment. Those in the experimental pond remained nearly constant. Phosphate concentration in the experimental pond was always higher than in the control pond. This was probably because few nonplanktonic algae were present. The bottom of the control pond was always covered with several algal forms that apparently utilized most of the available phosphates. Iron and manganese concentrations were appreciably higher in the experimental pond, probably because of leaching of these elements from the sand substrate. Additional data shown in table 27 indicate that the concentrations of sodium, potassium, zinc, and strontium differed little between the two ponds. These latter analyses were performed on water samples collected before the experiment began.

Dissolved oxygen concentrations included in table 28 were always higher in the control pond. This probably resulted from the greater mass of algae in the control pond and the subsequent photosynthesis that took place up to sampling time (3:00 p.m.). No consistent differences between the ponds were shown by pH or temperatures.

Data in table 29 indicate a gradual decrease in light intensity from the beginning to the end of the experiment. Mean weekly water temperatures (table 30) were nearly the same in the pond and in the fish tanks and demonstrated a gradual decrease from about 26° C in early September to about 19° C at the end of the

Table 25. Results of chemical analyses of experimental pond water [a]

Date	Days from start	Concentration, mg/l									
		Calcium	Magnesium	Iron	Manganese	Nitrogen (as NH_3)	Sulfate	Chloride	Total phosphate	Total hardness as $CaCO_3$	Total alkalinity as $CaCO_3$
6/20	—	33	23	0.20	(b)	(b)	42	11	0.36	180	110
7/5	—	19	20	0.08	(b)	(b)	40	23	0.03	130	90
7/29	—	18	19	0.36	0.04	0.11	33	13	0.07	120	82
8/1	2	22	18	0.45	0.20	0.35	35	12	(b)	130	110
8/3	4	23	16	0.56	0.20	0.55	35	12	0.10	120	110
8/7	8	22	18	0.44	0.20	0.47	34	12	0.10	130	110
8/11	12	29	18	0.36	0.11	0.15	34	13	0.25	150	130
8/15	16	25	19	0.32	0.09	0.15	32	13	0.05	140	130
8/23	24	25	20	0.32	0.10	0.10	37	14	0.11	150	130
9/6	38	22	19	0.34	0.10	0.20	32	14	0.07	140	120
9/20	52	21	19	0.28	0.11	0.20	32	14	0.13	130	120
10/4	66	27	18	0.68	0.08	0.12	32	10	0.19	140	120
10/18	80	24	22	0.12	0.06	0.15	31	8	0.13	150	120

[a] As determined by R. C. Kroner, Federal Water Pollution Control Administration, U.S. Department of the Interior, Cincinnati Water Research Laboratory, Cincinnati, Ohio.

[b] Below limits of detectability.

Table 26. Results of chemical analyses of control pond water [a]

Date	Days from start	Concentration, mg/l									
		Calcium	Magnesium	Iron	Manganese	Nitrogen (as NH_3)	Sulfate	Chloride	Total phosphate	Total hardness as $CaCO_3$	Total alkalinity as $CaCO_3$
6/20	—	30	19	(b)	(b)	—	34	11	0.07	160	130
7/5	—	21	21	0.03	(b)	0.27	30	23	0.07	140	110
7/29	—	32	20	(b)	(b)	0.05	28	13	0.05	160	120
8/1	2	32	20	0.08	(b)	0.22	34	13	0.10	160	140
8/3	4	34	21	0.02	(b)	0.20	36	13	(b)	170	150
8/7	8	40	23	0.03	(b)	0.15	40	12	0.10	190	170
8/11	12	37	25	0.12	(b)	0.07	38	14	0.05	190	170
8/15	16	46	23	0.10	(b)	0.10	40	14	0.07	210	180
8/23	24	41	24	0.10	(b)	0.10	40	15	0.03	200	180
9/6	38	42	28	0.04	(b)	0.05	33	16	0.07	220	200
9/20	52	35	24	0.06	(b)	0.17	31	15	0.10	190	170
10/4	66	39	18	(b)	(b)	0.05	39	10	(b)	170	150
10/18	80	36	24	0.06	(b)	0.05	42	13	0.05	190	150

[a] As determined by R. C. Kroner, Federal Water Pollution Control Administration, U.S. Department of the Interior, Cincinnati Water Research Laboratory, Cincinnati, Ohio.

[b] Below limits of detectability.

Table 27. Additional results of chemical analyses of pond water

Pond	Concentrations, mg/l			
	Sodium	Potassium	Zinc	Strontium
Experimental	10	8	0.03	0.14
Control	12	8	0.04	0.13

Table 28. Results of water sample analyses as determined at pond site [a]

Date	Days from start	Dissolved oxygen (mg/l)		pH		Alkalinity as $CaCO_3$ (mg/l)		Hardness as $CaCO_3$ (mg/l)		Temperature (° C)	
		Pond A	Pond B	Pond A	Pond B	Pond A	Pond B	Pond A	Pond B	Pond A	Pond B
7/31	1	9.4	19	9.0	9.4	98	120	120	150	29	([b])
8/2	3	9.6	19	9.0	9.4	100	120	130	150	30	30
8/6	7	7.0	14	8.7	8.8	110	140	140	180	30	30
8/8	9	9.2	18	8.8	9.0	140	140	180	170	34	32
8/10	11	11	17	8.9	9.0	150	290	140	180	29	29
8/13	14	10	16	7.8	8.7	120	160	150	160	28	27
8/16	17	9.6	17	8.7	8.9	140	170	150	210	27	27
8/20	21	13	18	8.3	10.2	150	150	150	190	30	30
8/22	23	12	16	8.1	9.8	170	190	150	200	31	30
8/24	25	14	16	([b])	([b])	160	160	160	190	31	30
9/4	36	11	12	9.0	8.5	140	200	150	220	29	28
9/7	39	10	15	9.2	9.5	140	140	140	170	25	25
9/24	56	12	18	9.6	9.0	140	170	170	190	20	20
9/25	57	12	17	8.9	8.8	200	200	170	200	20	20
9/26	58	12	16	8.4	8.5	160	160	160	240	19	19
9/28	60	12	18	9.2	8.9	130	160	170	200	19	18
10/2	64	9.6	14	8.6	8.4	140	160	150	240	17	17
10/5	67	12	18	9.0	8.6	130	170	150	190	20	20
10/8	70	12	14	9.4	8.9	140	130	160	190	20	20
10/10	72	11	18	8.8	9.0	180	160	140	120	22	23
10/12	74	13	19	8.9	8.5	140	180	140	180	23	23
10/15	77	10	19	8.8	9.0	100	200	150	200	25	25

[a] Pond A is the experimental pond. Pond B is the control pond. Water samples were collected at 3:00 p.m. Acidity determinations were always zero.

[b] Data not available.

experiment. Maximum air temperatures were higher in sunlight than in shade, but the means were approximately the same.

Water in the experimental pond was more turbid than water in the control pond. Control pond water was always sufficiently clear to permit seeing the pond bottom through several feet of water. The experimental pond water was so turbid that the bottom could be seen only through a few inches of water. This high

Table 29. Mean weekly light intensities [a]

Dates	Foot-candles	Dates	Foot-candles
7/29–8/4	520	9/9–9/15	390
8/5–8/11	490	9/16–9/22	360
8/12–8/18	490	9/23–9/29	360
8/19–8/25	450	9/30–10/6	(b)
8/26–9/1	390	10/7–10/13	340
9/2–9/8	420	10/14–10/20	320

[a] Obtained from recordings every 2 hours.
[b] Data not available.

Table 30. Weekly water and air temperatures [a]

Dates	Water (fish tanks)			Water (experimental pond)		
	Minimum	Mean	Maximum	Minimum	Mean	Maximum
7/29–8/4	21	26	30	21	27	31
8/5–8/11	21	26	31	22	28	33
8/12–8/18	19	23	27	19	25	30
8/19–8/25	20	25	29	21	26	30
8/26–9/1	18	26	29	18	27	31
9/2–9/8	16	23	28	18	24	29
9/9–9/15	18	22	25	18	23	27
9/16–9/22	13	18	24	14	19	26
9/23–9/29	13	16	18	14	17	18
9/30–10/6	(b)	(b)	(b)	(b)	(b)	(b)
10/7–10/13	17	19	21	17	19	22
10/14–10/20	14	18	22	14	19	22
	Air (in shade):			Air (in sun):		
7/29–8/4	12	22	37	11	22	37
8/5–8/11	10	22	37	10	22	37
8/12–8/18	9	19	30	9	19	33
8/19–8/25	12	22	32	11	23	40
8/26–9/1	13	23	32	12	23	36
9/2–9/8	6	18	28	5	19	31
9/9–9/15	9	19	30	9	19	34
9/16–9/22	2	13	25	2	14	31
9/23–9/29	5	13	20	5	13	25
9/30–10/6	(b)	(b)	(b)	(b)	(b)	(b)
10/7–10/13	9	17	27	9	18	28
10/14–10/20	4	15	27	3	15	27

[a] Obtained from recordings every 2 hours. Temperature in ° C.
[b] Data not available.

turbidity was caused by recirculation of the water, and more important, the behavioral characteristics of the bottom-feeding carp. The large numbers of phytoplankton present in the water also added to the turbidity of the experimental pond.

Phytoplankton in Experimental and Control Ponds

Large differences were observed in the abundance and numbers of generic forms of phytoplankton in the two ponds (tables 31, 32). The experimental pond contained more genera and many

Table 31. Experimental pond phytoplankton [a]

Date	Days from start	Phytoplankton (number of live cells per milliliter)					
		Blue-green algae	Coccoid green algae	Green flagellates	Other pigmented flagellates	Diatoms	Total
6/26	—	5,084 [b] (2)	9,786 (8)	446 (3)	312 (1)	5,938 (2)	21,566 (16)
7/5	—	445 (3)	934 (4)	134 (2)	268 (2)	5,863 (3)	7,644 (14)
7/29	—	3,032 (5)	9,251 (11)	334 (2)	803 (2)	6,311 (4)	19,731 (24)
8/1	2	1,849 (5)	12,747 (15)	490 (2)	535 (2)	5,238 (4)	20,859 (28)
8/3	4	6,742 (3)	25,873 (12)	994 (2)	704 (1)	13,124 (6)	47,437 (24)
8/7	8	985 (4)	4,701 (15)	102 (2)	0 (0)	5,511 (5)	11,299 (26)
8/11	12	3,170 (4)	18,961 (16)	85 (1)	980 (1)	6,226 (5)	29,422 (27)
8/15	16	4,407 (5)	8,590 (9)	178 (1)	430 (2)	5,180 (5)	18,785 (20)
8/23	24	10,440 (6)	7,846 (9)	88 (1)	0 (0)	4,075 (3)	22,449 (18)
9/6	38	3,567 (4)	8,654 (4)	267 (1)	714 (1)	7,248 (4)	20,540 (14)
9/20	52	10,882 (3)	5,976 (3)	357 (1)	446 (1)	2,407 (4)	20,068 (12)
10/4	66	16,433 (4)	4,013 (4)	736 (2)	1,160 (2)	3,565 (3)	25,907 (15)
10/18	80	85,522 (3)	2,296 (5)	0 (0)	803 (2)	3,255 (3)	91,876 (13)

[a] Analyses performed by Dr. L. G. Williams, Federal Water Pollution Control Administration, U.S. Department of the Interior, Duluth, Minnesota.

[b] Numbers in parentheses are the number of genera represented in a particular group.

Table 32. Control pond phytoplankton [a]

Date	Days from start	Phytoplankton (number of live cells per milliliter)					
		Blue-green algae	Coccoid green algae	Green flagellates	Other pigmented flagellates	Diatoms	Total
7/5	—	0	112	2,053	824	179	3,257
		[b] (0)	(3)	(3)	(2)	(2)	(10)
7/29	—	0	90	736	2,898	224	3,948
		(0)	(2)	(5)	(4)	(4)	(15)
8/1	2	401	134	134	3,987	692	5,348
		(3)	(2)	(2)	(2)	(6)	(15)
8/3	4	89	0	312	401	447	1,249
		(1)	(0)	(2)	(3)	(5)	(11)
8/7	8	67	67	200	1,137	380	1,851
		(1)	(2)	(3)	(3)	(5)	(14)
8/11	12	89	89	268	67	579	1,092
		(2)	(3)	(3)	(1)	(5)	(14)
8/15	16	89	22	157	580	446	1,294
		(1)	(1)	(2)	(2)	(4)	(10)
8/23	24	63	44	112	512	245	976
		(2)	(2)	(2)	(3)	(5)	(14)
9/6	38	0	0	156	70	225	451
		(0)	(0)	(2)	(1)	(5)	(8)
9/20	52	67	45	379	313	112	916
		(2)	(1)	(4)	(2)	(2)	(11)
10/4	66	0	44	0	22	225	291
		(0)	(1)	(0)	(1)	(4)	(6)
10/18	80	0	0	111	223	471	805
		(0)	(0)	(3)	(2)	(7)	(12)

[a] Analyses performed by Dr. L. G. Williams, Federal Water Pollution Control Administration, U.S. Department of the Interior, Duluth, Minnesota.

[b] Numbers in parentheses are the number of genera represented in a particular group.

more numbers of blue-green and coccoid green algae and diatoms than the control pond. This is at least partially due to competition between phytoplankton in the control pond and the abundant, nonrooted algae present in this pond. In many comparable situations, phytoplankton cannot successfully compete with nonrooted larger plants (*36*). This contention is supported by the phosphate concentration which was consistently lower in the control pond. The great numbers of diatoms, principally *Synedra* sp. and *Nitzschia* sp., in the experimental pond might also be attributable to a greater availability of silicon, required for the growth of diatoms

(*37*), as a result of the sand substrate. Other predominant genera of phytoplankton in the experimental pond were *Coelastrum, Agmenellum, Anacystis,* and *Gymnodinium.* Only one group demonstrated a definite seasonal pattern. The coccoid green algae gradually decreased in numbers and genera after early August, possibly because of the decrease in light during this period (table 29).

SUMMARY OF RADIOLOGICAL RESULTS

There was an initial rapid loss of cobalt 60, zinc 65, and cesium 137 from solution with the cobalt 60 and zinc 65 becoming principally associated with the bottom sediments and suspended solids, and cesium 137 with the bottom sediments. Strontium 85 was gradually removed from solution. Ten percent of the cobalt 60, 6 percent of the zinc 65, and 5 percent of the cesium 137 remained in solution after 4 days. At this time, 73 percent of the strontium 85 was still in solution.

More zinc 65 than any of the other test radionuclides was found in biological samples, except in some hard-parts fractions, such as shell and bone, in which strontium 85 activities usually exceeded those of zinc 65. The primary consumers—carp, snails, clams, and tadpoles—accumulated more of each radionuclide than did the predatory bluegill. In general, soft parts rapidly accumulated more radioactivity than hard parts, but gradually lost it as radionuclide concentrations in the water decreased. Clam and snail shells and fish bone usually accumulated zinc 65 and strontium 85 for almost the duration of the experiment.

Carp, snails, and clams remaining after the final sampling from the pond were placed in continuously replenished, uncontaminated water for 3 weeks, but no detectable radionuclide loss was observed. During this time the water temperature was about 15° C lower than at the end of the experiment, and the metabolic activity of these test organisms was greatly reduced. As a result, any loss of radionuclides would be inhibited.

Juvenile clams and snails accumulated more zinc 65 and strontium 85 than did adult clams and snails. However strontium 85 concentrations in the soft parts of clams were higher in adults. The maximum observed accumulation of strontium 85 occurred in the crayfish exoskeleton. Maximum radioactivities of the other test radionuclides were observed in the tadpoles.

Lampsilis juveniles grew much more than adults of that species. Carp in the pond increased in weight by nearly as much as 250 percent, while the weight of tank carp remained nearly constant.

The polyethylene liner proved to be very satisfactory for this experiment although care had to be taken not to puncture it. The fine sediments in the substrate were the most detrimental factor since they removed much of the added radionuclides and resulted in variable radionuclide concentrations in the substrate samples.

The rapid relocation of cobalt 60, zinc 65, and cesium 137 indicated that water samples should have been collected more frequently during the first week of the experiment in order to follow this distribution more closely. Water samples could also have been collected at various depths and locations in the pond to determine whether there were differential radionuclide concentrations in the pond despite recirculation of the water.

The effect of growth and species differences, as demonstrated by the clams and fish, is indicative of the information that is needed to obtain workable results of field investigations. These and other inherent physiological characteristics must be related to observed field data before general conclusions can be made. Also uptake variability within a species on each sampling day in this relatively uniform environment indicates that variability in the field could be even greater. Consequently field sampling programs should be based on large numbers of uniform samples, if possible. Experimental uptake data obtained by this laboratory were much less variable, partly because these latter experimental fish were of uniform size and were not fed during these tests. Differences in feeding are apparently important in determining radionuclide concentration by test organisms.

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BRUNGS, WILLIAM A., JR.: Distribution of cobalt 60, zinc 65, strontium 85, and cesium 137 in a freshwater pond.

U.S. Department of Health, Education, and Welfare, Public Health Service Publication No. 999-RH-24 (1967), 52 pp. (limited distribution).

ABSTRACT: Data were obtained on the physical, chemical, and ecological distribution of four radionuclides added to a small pond. The conditions were comparable to those in an accidental release of radionuclides to an impoundment. Cobalt 60, zinc 65, strontium 85, and cesium 137 were added to a 30,000-gallon pond, with a sand substrate, and containing experimental biota. The pond was lined with a single 8-mil sheet of black polyethylene. Sampling from the pond continued for 80 days. The quantities of radionuclides were determined with a gamma-scintillation spectrometer. Supplemental chemical and biological information on the artificial pond and an adjacent control pond provided a measure of the differences between these two environments. Results of the experiment were evaluated with regard to plans for future work.

After 4 days, 10 percent of the cobalt 60, 6 percent of the zinc 65, and 5 percent of the cesium 137 remained in solution. Cobalt 60 and zinc 65 were associated principally with suspended solids, and cesium 137 with bottom sediments.

(over)

ACCESSION NO.

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Biota
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Cobalt 60
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In general, soft parts of biota rapidly accumulated more radionuclides than hard parts, but gradually lost radioactivity as radionuclide concentrations in the water decreased. Clam and snail shells and fish bone usually accumulated zinc 65 and strontium 85 until almost the end of the experiment. More zinc 65 than any of the other test radionuclides was found in soft parts of biota. Strontium 85 activities usually exceeded those of zinc 65 in shell and bone.

Young clams and snails accumulated more zinc 65 and strontium 85 than did adult clams and snails. Strontium 85 concentrations in the soft parts of clams were higher in the adults. The maximum observed accumulation of strontium 85 occurred in the crayfish exoskeleton. Maximum activities of the other test radionuclides were observed in the tadpoles.

Environmental Health Series—Radiological Health

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Young clams and snails accumulated more zinc 65 and strontium 85 than did adult clams and snails. Strontium 85 concentrations in the soft parts of clams were higher in the adults. The maximum observed accumulation of strontium 85 occurred in the crayfish exoskeleton. Maximum activities of the other test radionuclides were observed in the tadpoles.

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